Typical Structure, Variety, and Multi-Scale Characteristics of Meiyu Front*

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ABSTRACT

Meiyu front plays an important role in summer rainfall in central China. Based on the GMS-5 satellite images, NCEP reanalyses (2.5°×2.5°) and final analyses (1°×1°) data, and meteorological conventional sounding observations, the horizontal and vertical structures of the Meiyu front were summarized using multiple diagnostic variables, including winds, temperature, jet stream, front, pseudo-equivalent potential temperature, divergence, vertical motion, static instability, etc. In this paper, four cases were selected and analyzed, two of which are in 26–28 June and 23 July 2002 during the Experiment on Heavy Rain in the Meiyu period in the lower reaches of the Yangtze River, and the others are in May and July 1998. The two cases in July 1998 and July 2002 are the secondary Meiyu front cases. The results show that the structures and characteristics of the Meiyu front are different for various cases, or at various places and time, or at various stages of one case, and the frontal characteristics can be converted from the polar front to the equatorial front. Because of the interaction of the different scale circulations in the high and low latitudes, the horizontal structure of the Meiyu front has various forms.

The results in this paper also show that the typical Meiyu front consists of a narrow band with a high gradient of potential equivalent temperature below 500 hPa, south of which is warm and moist air mass, and north of which is the transformed air mass from the midlatitude ocean or polar continent. Below the mid troposphere, south of the front blows southwesterlies, while north blows easterlies. The ascending motion and precipitation usually occur ahead of the Meiyu front. In the upper troposphere, the subtropical front is above the Meiyu front, but two fronts are separated. In addition, the upper westerly jet stream and the easterlies to the south of the Meiyu front result in the upper divergent flow field.

The multi-scale characteristics of the horizontal structure of the Meiyu front can be summarized as follows: in the upper troposphere, there exist the subtropical westerly jet, the easterlies to the south of the Meiyu front, and the South Asian high; at the mid troposphere, 500 hPa, the subtropical high over the West Pacific is the main weather system, to the northwest of which there are some short-wave troughs; in the lower troposphere, the planetary-scale southwesterly monsoon, the large-scale low-level southwesterly jet, and the mesoscale vortex or wave in the shear line are closely associated with the Meiyu front.

Key words: Meiyu front, typical structure, variety, multi-scale

1. Introduction

The flood caused by the Meiyu precipitation occurs often over the Yangtze-Huaihe River Basin, especially, during the summers of 1954, 1991, 1998, 2003, and 2007. In the 1930s, Zhu (1934) and Tu (1938) studied the relationship between Meiyu front and monsoon. Xie (1956) and Wang (1963) studied the thermal properties and structure of the Meiyu front, respectively. Since the 1990s, a large number of studies on the Meiyu front have been done. Zhang and Zhang (1990) made a summary of the studies on the Meiyu front. Wang and Tao (2002) analyzed the structure, formation, and development of the Meiyu front in a heavy rainstorm case occurring in June 1998. Zhou et al. (2005a, b) analyzed the synoptic features of the secondary Meiyu period and the thermodynamic and dynamical features of double front structures in 1998 over China. Liu et al. (2003) analyzed the structure of a typical Meiyu front in 1999 based on the NCEP 2.5°×2.5° analyses data. In Japan and Korea, there is a rainy period like Meiyu in China, which is called

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"Baiu" in Japan and "Chang-Ma" in Korea, respectively, and there are also a large number of studies on "Baiu" or "Chang-Ma" (Matsumoto et al., 1971; Ninomiya, 1984, 1999, 2000; Nagata and Ogura, 1991; Kato, 1989).

Xie (1956) classified the Meiyu precipitation as two types: one is the polar front precipitation in the late spring and early summer, and the other is the equatorial front precipitation in the mid-summer. Xie (1956) also proposed that both types of precipitation can be converted to each other, the precipitation in the mid-summer is influenced by the large-scale synoptic systems in the higher and lower latitudes, and the changes of the two large-scale synoptic systems are also independent. Yoshino (1965) divided the summer rainy season in East Asia into four stages based on the surface front position and the 500-hPa zonal winds. The first stage is the pre-flood-season in South China (Tao, 1980), called the forerunner of Baiu in Japan. The second stage is the onset phase of the Meiyu over central China and Japan. Stage 3 is the climax of the Meiyu season over East Asia, and stage 4 is the end of monsoon precipitation over East Asia, and the 500-hPa westerly wind axis retreats to 40°N. Lei et al. (1981) proposed that the energy front can be used to replace or complement the definition of the shear line and the Meiyu front, and they got three types of energy front during the Meiyu period as follows: the backward-slant front, the forward-slant front, and the perpendicular front. Zhang et al. (2004) summarized the Meiyu front over central and South China as three types and compared them with each other.

Zheng et al. (2008) reviewed the characteristics and structure of the synoptic-scale Meiyu front based on the studies in the past decades. Many studies show that the structure of the Meiyu front is very complicated, and has a multiform feature. The characteristics and structure of the Meiyu front may be different for various cases, or over different regions, or at different stages of one Meiyu front. The properties of the Meiyu front can be converted from the polar front to the equatorial front and its structure can have striking differences.

Based on the previous studies, the Meiyu front has some basic features and the synoptic definition of the Meiyu front is as follows (Zheng et al., 2008): there is one narrow rain band thousands of kilometers long across East Asia and the West Pacific; the Meiyu rain band advances and retreats with the Asian monsoon, and the Meiyu front is the frontal surface between the monsoon air mass and the others; the Meiyu frontal area is one band with a high gradient of potential equivalent temperature ($\theta_{\rm e}$). Therefore, the region of the Meiyu and the Meiyu front extends from the Yangtze-Huaihe River Basin to South China and Taiwan, and the period of the Meiyu can be traced from the summer back to May. Because of the extending synoptic definition of the Meiyu front, the properties of the Meiyu front are different in various places or during different periods.

Although the Meiyu front has a multiform feature, most of studies gave only one or several sides of the typical Meiyu front structure, thus the comprehensive and integral structure of the typical Meiyu front has not been yielded. The aim of this paper is to obtain the integral typical structure and the synoptic scale circulation model of the Meiyu front, in which the various variables (winds, temperature, jet stream, front, pseduo-equivalent potential temperature, the shear line, divergence, vertical motion, static stability, etc.) couple with each other, by means of detailedly analyzing one typical Meiyu case. To show the multiform structure of the Meiyu front and the mulit-scale characteristics of its horizontal circulation, we also present some other Meiyu front cases similar to the polar front or the equatorial front. The typical Meiyu front usually persists over the middle and lower reaches of the Yangtze River from early or mid June to early July. However, the Meiyu front similar to the polar front occurs more often during the onset period of the East Asian monsoon or during May−June, and the Meiyu front like the equatorial front happens usually during July−August. The selected Meiyu cases in this paper occurred in the summers of 1998 and 2002.

2. Data and method

The data used in this paper include the conventional meteorological sounding data, the NCEP (National Centers for Environmental Prediction) reanalysis and final analysis data, and the infrared (IR) satellite imagery from GMS-5 (Geostationary Meteorological Satellite 5) of Japan. The NCEP reanalysis data are at 6-h intervals, and at the horizontal resolution of 2.5°×2.5°, and have 11 standard levels in the troposphere. The NCEP final analysis data are also at 6-h intervals, and at the horizontal resolution of 1°×1° and at the vertical resolution of 25 hPa between 1000 and 900 hPa and of 50 hPa between 900 and 100 hPa.

The GMS-5 IR imagery is presented to show the appearance and development of the Meiyu front. The conventional meteorological sounding data are combined with the NCEP reanalysis or final analysis data to diagnose and analyze the horizontal and vertical structures of the Meiyu front. The multi-scale conceptual model of the Meiyu front is given based on the stream fields at 200, 500, and 850 hPa.

In the vertical cross section, the pseudo-equivalent potential temperature ($\theta_{\rm se}$) is given to determine the Meiyu front position, and the temperature is also presented to show whether the Meiyu front is similar to the polar front. The zonal wind component is presented in the meridional vertical cross section to display the zero isoline of the component, the subtropical upper westerly jet stream and easterly jet stream, and the zero isoline of the component can be used to denote the vertical axis of the shear line at low levels. In addition, the meridional wind component is given in the zonal vertical cross section.

Because the precipitation is a moist adiabatic process during the Meiyu period, the vertical axis of high $\theta_{\rm se}$ in the vertical cross section combining with the ascending motion can be used to display the position and intensity of the Meiyu rain band. The horizontal axis of low $\theta_{\rm se}$ in the vertical cross section is analyzed to show the air depth with convective instability.

It is important to note that we use the 1998 NCEP 2.5°×2.5° data and the sounding data to calculate the diagnostic variables because there are no NCEP 1°×1° data in 1998. For the 2002 cases, we only use the 2002 NCEP 1°×1° data to calculate the diagnostic variables, and the sounding data are used to display as the observations.

3. Typical Meiyu front in 2002

3.1 Overview

The typical Meiyu front case occurred during 26–28 June 2002 in the lower reaches of the Yangtze River. In the satellite IR image at 0000 UTC 27 June 2002 (figure omitted), the pattern of the Meiyu cloud band over the Yangtze River Basin has an obvious fluctuation, the east part of which protrudes to the north and the west part to the south. This pattern is very similar to the frontal wave at the cyclone-developing stage. There were already some convective cloud clusters even though it was early morning when convection is the least inactive, showing that the atmosphere was very unstable. In the afternoon, the convection became more active, and in the evening, the typical Meiyu front cloud band formed over the south of the Yangtze River, in which there were several convective cloud clusters (Fig.1a). The Meiyu front cloud band was from the China-Burma boundary through the upper and lower reaches of the Yangtze River to Japan, and moved slightly southward in the development.

At the developing stage of the Meiyu front at 1200 UTC 26 June (figure omitted), there was a strong high-$\theta_{\rm se}$ area extending from India to the upper reaches of the Yangtze River and South China, in the east part of which the southerlies blew, and there was a warm-front shear line between the southerlies and southeasterlies. The dense $\theta_{\rm se}$ isolines in the northeast part of high-$\theta_{\rm se}$ area ran from northwest to southeast, which intersected with the shear line that was from west-southwest to east-southeast. However, the $\theta_{\rm se}$ frontal area was consistent with the rising area at 500 hPa and the convective cloud clusters shown in the satellite IR images.

At 0000 UTC 27 June (figure omitted), the high-$\theta_{\rm se}$ area extended to the middle reaches of the Yangtze River and developed to an east-west high-$\theta_{\rm se}$ tongue. Meanwhile, the characteristics of the shear line had changed, to the north of which were easterlies and to the south were southwesterlies. The maximum wind speed of southwesterlies reached 18 m s^{-1} and turned to a strong low-level jet. The direction of the θ_{se} front is similar to that at 1200 UTC 26 June, and the frontal area and the shear line did not superimpose yet.

At 1200 UTC 27 June (Fig.1b), the high-θ_{se} area and the shear line were very similar to those at 0000 UTC 27 June, but the θ_{se} front became to run from east to west, thus the frontal area and the shear line nearly superimposed and were consistent with the rising area at 500 hPa, and the Meiyu front became a typical one.

It is important to note that the 850-hPa temperature gradient was yet obvious even though the temperature gradient was less than the θ_{se} gradient. It shows that there was a transformed polar air mass to the north of the Meiyu front. Viewing the observational winds and the isotherms in Fig.1b, the cold air to the north of the Meiyu front was from the midlatitude cold ocean in the east. The Meiyu front moving slowly southward also illustrates that the cold air also had certain intensity in the Meiyu period.

3.2 Vertical structure

The evolution of 850-hPa θ_{se} (figure omitted) shows that the high-θ_{se} gradient band moved from 30°–35°N to the south of 30°N, thus we selected the two cross sections along 110° and 115°E to display the different structures of the Meiyu front over different regions.

3.2.1 Vertical structure before Meiyu front formation

In the vertical cross section along longitude 110°E at 1200 UTC 26 June (figure omitted), the θ_{se} isolines show that there was a frontal area slantwise northward throughout the whole troposphere coupling with strong rising motion and the high θ_{se} axis over 35°–40°N. An upward angle of isotherms shows that there was certain temperature contrast across the Meiyu frontal area. The wind speed above the frontal area turned to intensify and the jet formed at about 200 hPa, and it also shows that the front had obvious baroclinicity. However, the upper front did not extend to the ground and was located above 850 hPa. The horizontal zero isoline of zonal wind component shows that there was not a shear line at low levels. All above mentioned reveal that the Meiyu front did not form yet along 110°E.

In the vertical cross section along 115°E at 1200 UTC 26 June (figure omitted), there were also the subtropical upper front and the subtropical jet stream. In the lower-mid troposphere (below 500 hPa), the θ_{se} isolines similar to an equatorial front slanted southward over 27°–35°N, but the zero isoline of westerly was nearly horizontal and the upward motion was also much weaker over 30°–35°N.

3.2.2 Vertical structure of Meiyu front at onset

At 0000 UTC 27 June, the band of much denser θ_{se} isolines at 850 hPa began to form, and the Meiyu front obviously appeared in the vertical cross sections along 110° and 115°E. In the mid-lower troposphere there existed the band of much denser θ_{se} isolines and a shear line below 700 hPa, and the upward motion area was upright, both the strength and extent of which vastly intensified. Accompanied with the southwesterly monsoon intensifying and the wind speed attaining 18 m s^{-1} at 0000 UTC 27 June, the 5–10-m s^{-1} westerly component appeared to the south of the low-level shear line in the vertical cross sections.

Because the formation of the Meiyu front was closely related to the cold air activity, even though the Meiyu front was nearly perpendicular, it slanted slightly northward. The mentioned above reveals that the Meiyu front remained yet certain baroclinicity, which was also revealed by the direction of isotherms. The fluctuation of the Meiyu cloud band in the IR satellite images may be also associated with the atmospheric baroclinicity. The rising area in the 115°E vertical cross section was much wider than that in the 110°E vertical cross section. There existed two basic flows of zonal wind component in the upper troposphere, one of which was the subtropical westerly jet stream over 35°–40°N, and the other was the easterly jet stream over 20°–25°N. It is worthwhile to note that the rising motion associated with the Meiyu front was located in the westerly side, demonstrating that the Meiyu cloud band was related to the divergence field in the east of the subtropical high ridge.

3.2.3 Vertical structure at mature stage of Meiyu front

At 1200 UTC 27 June, the typical Meiyu front characteristics became much more obvious, such as the high-θ_{se} tongue at 850 hPa and its strong gradient in the north, the zonal rising band at 500 hPa, and the zonal Meiyu cloud band in the satellite IR images. The satellite IR images also show that there were several intensive mesoscale convective systems (MCSs) (Fig.1a). The vertical cross sections (Fig.2) show that the Meiyu front was below 500 hPa and separated from the subtropical upper front. The Meiyu front was steeper than the subtropical upper front and slanted slightly southward. The mentioned above reveals that the typical Meiyu front had much weaker bacroclinicity. In the planetary boundary layer below 1-km altitude, the Meiyu front slanted obviously southward, showing that the Meiyu front is very similar to the equatorial front (Wang, 1963).

In the lower troposphere, the Meiyu front was superimposed on the shear line, and the subtropical upper front was closely related to the westerly jet stream. The rising area was located ahead of the Meiyu front and coupled with the high-θ_{se} tongue, revealing that the Meiyu rain band was situated to the south of the Meiyu front. The rising area in the 115°E cross section was much wider than that in the 110°E cross section, and it shows that the MCS over the former region was very stronger than that over the latter region. It is important to note that there was a low-level southwesterly jet to the south of the Meiyu front, the rising motion was located between the upper westerlies and easterlies, and the air masses in the two sides of the Meiyu front were both convectively unstable, but the air mass to the south was even more unstable.

3.2.4 Vertical structure model of typical Meiyu front

The above analyses show that the structure and characteristics of the Meiyu front were different at different places and time, or at different stages. Based on the 115°E cross section at 1200 UTC 27 June 2002, the 3D model of typical Meiyu front is summarized in Fig.2. The typical characteristics of the Meiyu front are as follows:

(1) The basic characteristic of the typical Meiyu front is that the front consists of the strong horizontal gradient of θ_{se} below the middle troposphere (500 hPa), and it is displayed on both isobaric weather maps and vertical cross sections. In the vertical cross sections, the slope of the Meiyu front is very steep, sometimes perpendicular, and sometimes it slants southward, especially in the planetary boundary layer below 850 hPa.

(2) The air mass to the south of the Meiyu front is warm, moist and of high θ_{se}, and to the north is the transformed air mass from the midlatitude ocean or polar continent. On this occasion, there is a high gradient of temperature between both sides of the Meiyu front. However, on some occasions, the transformed air mass can be replaced with the continental warm dry air, and then there is almost no temperature contrast between both sides of the Meiyu front. Furthermore, sometimes the temperature to the north can be higher than that to the south.

(3) To the south of the Meiyu front is the southwesterly monsoon and to the north the easterly in the lower troposphere. In most occasions, there is a shear line associated with the Meiyu front below 700 hPa. The wind speed of the southwesterlies can be more than 12 m s^{-1} and can form a low-level jet to the south of the Meiyu front, and it transports large amounts of water vapor into the rainfall area.

(4) The ascending motion and precipitation mainly occur in the front area of the Meiyu front. This is because the synoptic conditions are favorable for the convection occurrence and development when the warm moist air transported by the southwesterlies converges and ascends near the shear line. On the other hand, the air is potentially unstable in the monsoon air mass.

(5) There exists a subtropical upper front above the Meiyu front in the upper troposphere, but the subtropical front is separated from the Meiyu front and lies to the south of the Meiyu front. The temperature contrast between both sides of the subtropical front is more obvious than that of the Meiyu front. In addition, the westerly jet stream is closely associated with the subtropical upper front. The latent heat released from the rainfall of the Meiyu front maybe causes the obvious baroclinicity of the subtropical upper front.

(6) To the south of the Meiyu rain band are the tropical upper easterlies in the upper troposphere.

Both the easterlies and the subtropical upper westerlies constitute the upper convergent field.

3.3 Synoptic-scale model of typical Meiyu front

Because the Meiyu front occurs in the special atmospheric circulation, it is closely related to the planetary-scale circulation systems in the Northern Hemisphere in summertime. In addition, because the Meiyu frontal system is thousands of kilometers long in horizontal, there are some smaller-scale weather systems inside the Meiyu frontal system. Zhang et al. (2002) proposed that there are four weather systems influencing the Meiyu front: the subtropical high, the monsoon surge, the cold air from the north, and the meso-β-scale plateau trough from the northeastern Tibetan Plateau. Therefore, the horizontal structure of the Meiyu front is not only referred as the strong horizontal gradient band of θ_{se} and the shear line between southwesterlies and easterlies in the lower troposphere, but also including the large-scale circulation systems related to the Meiyu front and the MCSs inside the Meiyu front. Moreover, the Meiyu frontal system is located both in the lower and mid-upper troposphere. Accordingly, the horizontal circulation of the Meiyu front must be of multiple scales, and the circulations in the lower troposphere couple with those in the upper troposphere. In this paper, we use the case at 1200 UTC 27 June 2002 to present the synoptic-scale horizontal structure of the Meiyu front.

Figure 3 gives the synoptic-scale model of the horizontal circulation of the Meiyu front. Figure 3 shows that there are three planetary-scale circulation systems in the upper troposphere: the subtropical upper westerly jet stream, the upper easterly, and the South Asian high. The divergent field composed of the three planetary-scale circulation systems in the upper troposphere gives the outflow mechanism of the rising air in the Meiyu frontal system. There is the West Pacific subtropical high in the mid troposphere, to the northwest of which there may be some active short-wave troughs in the westerlies. In the lower troposphere, the synoptic systems associated with the Meiyu front include the planetary-scale monsoon (the South China Sea monsoon and the Indian monsoon), the low-level southwesterly jet stream, the shear line, and the mesoscale waves or vortices in the shear line. The synoptic systems associated with the Meiyu front in the lower troposphere make the Meiyu front possess the strong horizontal gradient band of θ_{se} and provide the Meiyu precipitation with plenty of water vapor and the convergent field.

4. Slantwise secondary Meiyu front in 2002

4.1 Horizontal and vertical structures

The heavy precipitation event on 23 July 2002 was caused by the secondary Meiyu front. The satellite IR images show that the rain band had the common characteristics of the Meiyu front, but the direction of the cloud band ran from southwest to northeast mostly along meridian. Therefore, the cloud band seems very different from the Meiyu cloud band in appearance and it is very necessary to examine its structure and characteristics.

Figure 4b (850-hPa weather map) shows that the southwest-northeast cloud band in the satellite IR images was consistent with the strong horizontal gradient band of θ_{se}. The axis of high θ_{se} ran northeastward from China-Vietnam boundary to the south of Korean Peninsula. The shear line between northeasterlies and southwesterlies was just located ahead of the Meiyu front, and the wind speed of southwesterlies attained 16 m s^{-1}. Therefore, the front was a Meiyu front in view of the distribution of temperature, humidity, and winds at 850 hPa, but its direction ran to a great extent along meridian.

Because the Meiyu front on 23 July 2002 did not run along parallels, Fig.5 presents the vertical cross sections along 118°E and 32°N to examine the vertical structure of the Meiyu front. In the vertical cross section along 118°E, the structure of the Meiyu front was to some degree similar to that in July 1998 (see Section 5). The temperature contrast in both two cases was very little and the frontal slope was steep, but the frontal slope in 2002 was nearly perpendicular and did not slant southward. In the 2002 case, the vertical axis of the shear line between easterlies and westerlies was almost superimposed on the lower boundary of the Meiyu front in the lower troposphere, but the wind

speed of easterlies was very small because the winds behind the Meiyu front were mainly northerlies. However, the Meiyu front in July 1998 was vastly separated from the shear line in the lower troposphere.

In the vertical cross section along 32°N, we use the meridional component of wind to replace its zonal component. In Fig.5b, the winds on two sides of the Meiyu front were northerlies and southerlies separately, and its vertical extent almost occupied the whole troposphere. However, the temperature contrast between two sides of the front was not obvious; consequently, the frontal slope was very steep and slanted slightly westward.

The analyses about the vertical cross sections show that the front in July 2002 was still of the Meiyu front during the monsoon peak period and similar to the equatorial front. The temperature contrast between two sides of the front was very few and the fontal slope was almost steep. Although it blew northerlies behind the Meiyu front, the cold air was not marked because it was in mid-summer. It is important to note that the frontal area in the mid-troposphere did not reach the ground in Fig.5b, and there was a low-θ_{se} area below 850 hPa and the direction of isotherms was also to some extent slantwise. Therefore, the cold air could also be active below 1-km altitude above ground, but this needs to be further studied.

4.2 Multi-scale horizontal structure of Meiyu front

The case in July 2002 shows that the front along meridian in the monsoon peak period also has the common characteristics of the Meiyu front. The satellite IR image (Fig.4a) also shows that the Meiyu front was not only of multiple scales, but also produced by the synoptic system interaction between the higher and the lower latitudes. The 500-hPa weather map given in Fig.6 illustrates this well. Figure 6 shows that the slantwise Meiyu front was closely associated with the long-wave trough, and ridge in the midlatitude westerlies and the northeast-southwest axis of the subtropical high. The three vortices in the long-wave trough were fully consistent with the three waves in the Meiyu front, and it adequately reveals that the disturbance in the Meiyu front was produced by the synoptic system interaction between the higher and the lower latitudes.

The satellite IR image animation and Fig.4a show that the Meiyu frontal heavy rain occurred at the boundary between the synoptic systems over the higher and the lower latitudes; there was a long-wave trough over the higher latitudes; the Meiyu front, short-wave trough and mesoscale cloud clusters lay over the midlatitudes; the subtropical high and typhoons were located over the lower latitudes. The northeast-southwest long-wave slantwise rain band moved eastward slowly, in which the three short-wave disturbances moved northward rapidly. There were two low vortices behind the large-scale rain band. In the rear of the low vortex, there were descending northerlies, and in the front part was rising southerlies. To the south of the rain band was the subtropical high. There were three tropical cyclones over the lower latitudes, and the MCSs occurred at the boundary between the synoptic systems over the higher and lower latitudes.

5. Secondary Meiyu front in 1998

The precipitation during the Meiyu period of 1998 is one of the most intensive precipitation events in the half a century, especially, the precipitation during the last ten days of July 1998 was much heavier, and the rainfall in one hour at one station in eastern Hubei Province was over 80 mm. Therefore the case on 22 July 1998 was selected to illustrate the characteristics

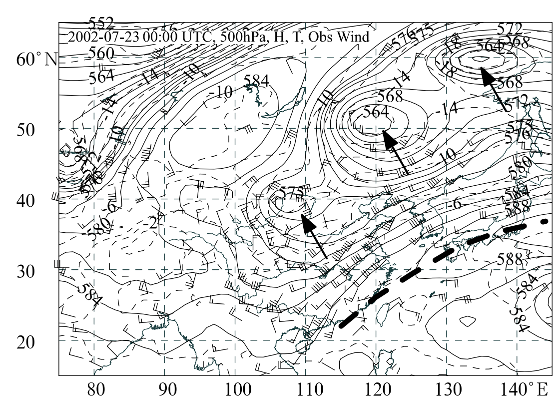

Fig.6. The 500-hPa height, temperature, and wind fields at 0000 UTC 23 July 2002. Thick arrows denote the circulation of low vortex.

of the secondary Meiyu front in this paper.

Based on the satellite IR image in Fig.7a, we can find that the cloud band on 22 July 1998 over the middle and lower reaches of the Yangtze River was the Meiyu frontal cloud band. The reasons are as follows: i) the cloud band was along parallels from 105° to 145°E and thousands of kilometers long; ii) there were several southwest-northeast convective cloud lines to the south of the long cloud band, which can be traced to northern South China Sea and the Bay of Bengal, indicating that rain band is associated with southwest monsoon; and iii) the clear-air area within the subtropical high to the south of the cloud band shows that the long cloud band was not in the intertropical convergence zone. Therefore, the long cloud band on 22 July 1998 accords with the first two terms of the Meiyu front definition in the study of Zheng et al. (2008).

The third term of the Meiyu front definition in the study of Zheng et al. (2008) is that the Meiyu front is the strong horizontal gradient band of θ_{se} to the north of the air tongue with high temperature and moisture. The 850-hPa θ_{se} distribution (Fig.7b) shows that there was a high-θ_{se} tongue from Northeast India through the upper reaches of the Yangtze River to the East China Sea, to the north of which was the strong horizontal gradient band of θ_{se}. Therefore, the long cloud band on 22 July 1998 conforms to the third term of the Meiyu front definition in the study of Zheng et al. (2008).

It is important to note that the high-θ_{se} axis in Fig.7b was also the shear line between southwesterlies

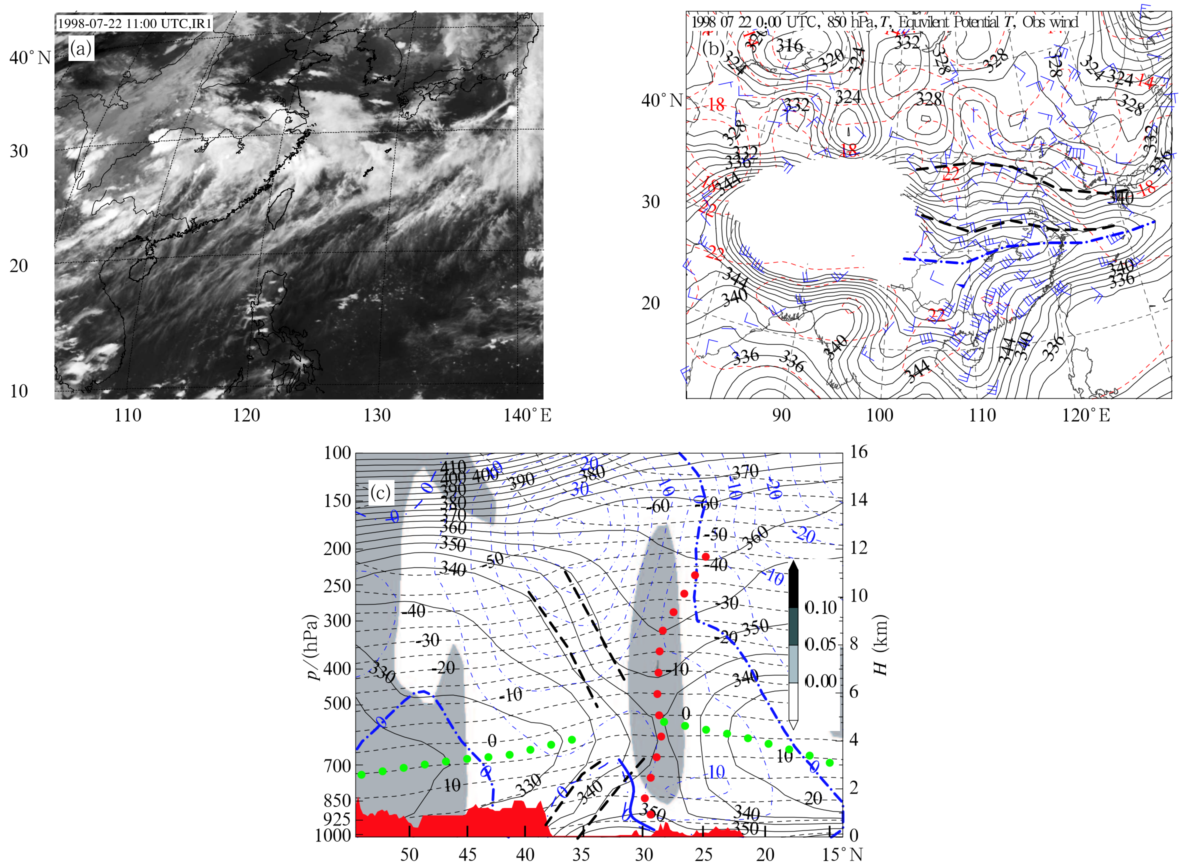

Fig.7. IR cloud image of GMS5 at 1100 UTC (a), temperature, θ_{se}, and wind fields of 850 hPa at 0000 UTC (b), and vertical cross section along 115°E (c) on 22 July 1998. In Fig.7b, θ_{se} isolines are solid, at intervals of 2 K; isotherms are dashed, at intervals of 2°C; thick dashed lines are Meiyu front; thick dot-dashed line is the axis of high θ_{se} and so is the wind shear line; legends in Fig.7c are same as in Fig.5a, and the blue thick line denotes the vertical axis of shear line.

and easterlies and located to the south of the strong horizontal gradient band of θ_{se}. The distance between the shear line and the strong horizontal gradient band of θ_{se} was about 500 km. The high-θ_{se} axis or the shear line was superimposed on the Meiyu cloud band in Fig.7a. In other words, the Meiyu front was separated from the rain band and the shear line, and the precipitation occurred ahead of the Meiyu front. In addition, there was no isotherm in the high-θ_{se} tongue and the strong horizontal gradient band of θ_{se}. It illustrates that the temperature was quite uniform in the Yangtze River Basin and the middle-lower reaches of the Yellow River and the Meiyu front was caused only by the humidity contrast. Consequently, the Meiyu front in the monsoon peak period is very different from that at the onset of monsoon and the typical Meiyu front.

The vertical cross section along 115°E in Fig.7c clearly illustrates that the secondary Meiyu front was very different from the typical Meiyu front and that at the onset of monsoon. The secondary Meiyu front has some characteristics of the equatorial front. The differences between the secondary Meiyu front and the typical Meiyu front are as follows: i) the secondary Meiyu front slants southward in the lower troposphere, and the subtropical front in the upper troposphere slants still to the north; ii) the shear line in the lower troposphere is far away from the secondary Meiyu front, and they do not match with each other, and the vertical axis of the shear line slants to the north on the whole; and iii) the rising area is located in front of the shear line, thus the rain area is far away from the secondary Meiyu front and lies to the south of the front.

6. Meiyu front at the onset of monsoon

Heavy rain occurred during 23–24 May 1998 and was captured by the experiment of the heavy rain in South China, and this case was a typical Meiyu front at the onset of monsoon. We can find that the front was composed of the strong horizontal gradient band of θ_{se} on the 850-hPa weather maps (Fig.8) and the vertical cross sections (Fig.9). Both the direction and upward angle of the isotherms on the vertical cross sections show that there was obvious temperature contrast between two sides of the Meiyu front, the Meiyu front had some characteristics of a polar front, and the front slanted northward and extended upward to the tropopause with about 10-km altitude. The front moved southward markedly from 23 to 24 May 1998.

The high-θ_{se} axes plotted as dot-dashed lines in Figs.8 and 9 show the warm and moist air mass in front of and above the Meiyu front. The high-θ_{se} axes in the vertical cross sections of Fig.9 slanted northward below 700 hPa, illustrating that the low-level monsoon air rose above the Meiyu front. Above 700 hPa, the high-θ_{se} axis was perpendicular and there was a low vertical gradient of θ_{se}, illustrating that the θ_{se} above

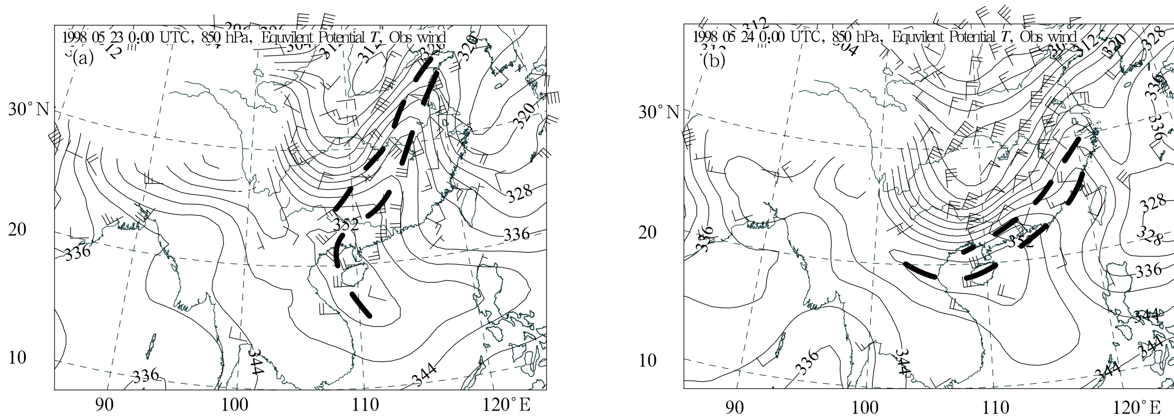

Fig.8. The 850-hPa θ_{se} distributions at (a) 0000 UTC 23 and (b) 0000 UTC 24 May 1998. Dashed line is the shear line, and dot-dashed line is the axis of high θ_{se}.

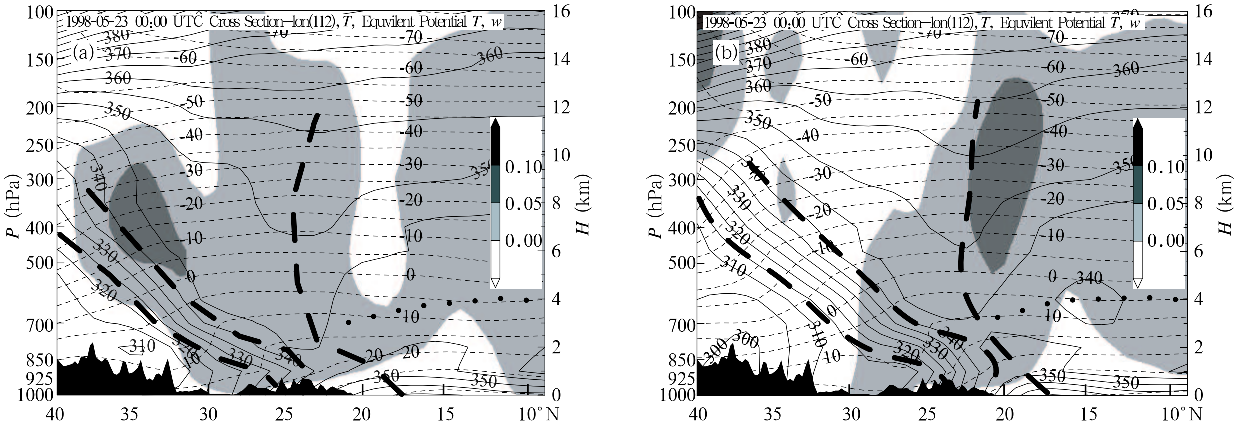

Fig.9. As in Fig.8, but for the vertical cross section along 112°E. Black shaded areas are the topography; isotherms are the thin dashed lines with intervals of 5°C; θ_{se} isolines are black thin solid lines with intervals of 5 K; gray shaded areas are the upward motions with intervals of 0.05 m s^{-1}; thick dashed lines are the upper and lower boundaries of the front; dot-dashed line is the axis of high θ_{se}; dot line is the axis of low θ_{se}.

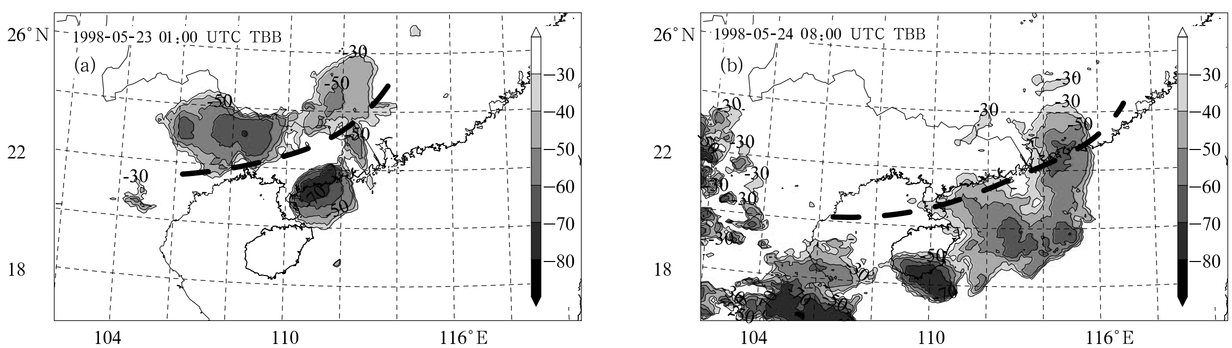

Fig.10. The IR TBB distributions of GMS5 at (a) 0100 UTC 23 May and (b) 0800 UTC 24 May 1998. TBB isolines start from –30°C with intervals of 10°C, and thick dashed lines denote the front.

the Meiyu front was constant in the moist adiabatic precipitation process. The low-θ_{se} axes in the vertical cross sections of Fig.9 show that the air was convectively unstable because the θ_{se} became lower with increasing altitudes and it is the necessary condition for the heavy convective precipitation.

The vertical motion distribution in the two vertical cross sections in Fig.9 was somewhat different from each other. The strongest rising motion on 23 May was located behind the surface front and above the upper front, illustrating that the rising motion was closely related to the baroclinicity of the Meiyu front. However, the strongest rising motion on 24 May lay ahead of the front, and there was a high-θ_{se} tongue below the center of the rising motion, therefore, the rising motion may be associated with the convection ahead of the front.

The IR TBB distribution from GMS-5 (Fig.10) shows that there were strong meso-α-scale convective systems or meso-β-scale convective systems on and ahead of the Meiyu front at the onset of monsoon. However, the contrast between the IR images on 23 and 24 May shows that the precipitation occurred behind the front on 23 May, but the precipitation ahead of the front on 24 May. The MCSs were consistent with the upward motion distribution in the cross sections (Fig.9).

The contrast between the cross sections in Fig.9

shows that the strongest rising area moved from behind the front to ahead of the front and the slope of the front and the high-θ_{se} axis also turned more perpendicular. It shows that the Meiyu front may have the tendency from a polar front to an equatorial front when it moved southward at the onset of monsoon.

This case was simulated using the mesoscale numerical model (MM5) (Zhou et al., 2003) and the 3D virtual image was made using the simulation data and clearly displayed that the Meiyu front similar to a polar front slanted to the cold air mass at the onset of monsoon, the monsoon air mass ahead of the front had convective instability, and the MCS was located on and ahead of the front.

7. Conclusions and discussions

Based on the synoptic definition of the Meiyu front in the study of Zheng et al. (2008), we selected and diagnosed several representative Meiyu front cases to reveal the typical structure, multi-scale characteristics, and variety of the Meiyu front. Although the multi-stage of the Meiyu front also reflects the variety feature of the Meiyu front in Yoshino's study (Yoshino, 1965), the selected cases in this paper not only show that the Meiyu fronts at different stages have different characteristics, but also show that the different Meiyu fronts at the same stage have different characteristics, e.g., the secondary Meiyu front in 1998 was different from that in 2002.

Based on the multi-variable (e.g., winds, temperature, jet stream, front, θ_{se}, divergence, vertical motion, and static instability) configuration of the typical Meiyu front, the comprehensive dynamical and thermodynamic characteristics of 3D structure of the typical Meiyu front are summarized as follows: i) the basic characteristic is that the front consists of the strong horizontal gradient of θ_{se} below the mid troposphere; ii) there is the warm and moist air mass with high θ_{se} to the south of the Meiyu front and there is the cold and low-humidity transformed air mass to the north of the front; iii) to the south of the front are southwesterlies and to the north of the front easterlies; iv) the rising motion is mainly located ahead of the front; v) there exists a subtropical upper front above the Meiyu front in the upper troposphere, but the subtropical front is separated from the Meiyu front and lies to the south of the Meiyu front; and vi) the tropical upper easterlies in the upper troposphere lie to the south of the Meiyu rain band, together with the subtropical upper westerlies construct the upper convergent field.

Comparing the vertical structure of the typical Meiyu front in this paper with the schematic of the Meiyu front in the study of Liu et al. (2003), their basic characteristics are consistent with each other. However, the schematic in the study of Liu et al. (2003) did not present the configuration of the upper and lower winds. In addition, they regarded the subtropical upper front as a part of the Meiyu front, but we do not agree with them. This is because that the subtropical upper front is in general associated with the subtropical upper jet stream, called jet-front system. Therefore, in order to emphasize the reasonable vertical configuration of the jet and upper front, which conform to the relationship of thermal wind, we gave the subtropical upper front in the typical Meiyu front structure.

Three types of Meiyu front different from the typical Meiyu front are summarized as follows: i) one type of Meiyu front with lower baroclinicity is northeast-southwest oriented and nearly perpendicular and is produced by the synoptic system interaction between the higher and the lower latitudes; ii) the Meiyu front like an equatorial front is perpendicular or slants southward, because the air has little baroclinicity in the monsoon peak period; and iii) the Meiyu front at the onset of monsoon has stronger baroclinicity and smaller slope and is similar to a polar front. Because these three types of Meiyu front are different from each other in the direction, the slope of front, the temperature constrast, the shear line configuration, and so on, the Meiyu front has a multiform feature.

The horizontal structure of the Meiyu front is not only referred to itself but also includes the large-scale circulation systems associated with the Meiyu front and the shear line and the MCSs within the Meiyu front, however, it includes the systems not only in the lower troposphere but also in the upper troposphere. Based on the circulations associated with the typical Meiyu front and the secondary Meiyu front, the multi-scale characteristics of the Meiyu front are as follows: i) there are three planetary-scale circulation systems in the upper troposphere, the South Aisan high, the subtropical westerly jet stream and the tropical easterlies; ii) there is the West Pacific subtropical high in the mid troposphere, to the northwest of which there may be some active short-wave troughs or low vortices in the westerlies; and iii) in the lower troposphere, the synoptic systems associated with the Meiyu front include the planetary-scale monsoon, the low-level southwesterly jet stream, the shear line and the mesoscale waves or vortices in the shear line.

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